

WHAT IS CLAIMED IS:

1. A method for shifting the bandgap energy of a quantum well layer comprising:
introducing ions into a quantum well structure at an elevated temperature and
a dose of greater than $1 \times 10^{12} \text{ cm}^{-2}$, the quantum well structure comprising:
an upper barrier layer;
a lower barrier layer; and
a quantum well layer disposed between the upper barrier layer and the
lower barrier layer; and
thermally annealing the quantum well structure;
whereby quantum well interdiffusion is induced and the bandgap energy of the
quantum well layer is shifted.

2. The method of claim 1, wherein the elevated temperature in the range of from
about 200 °C to near the crystal damage temperature.

3. The crystal damage temperature of claim 2 is about 750°C for InP/InGaAsP
materials and is about 950°C for GaAs/AlGaAs materials.

4. The method of claim 1, wherein the introducing step creates crystal site
vacancies in the quantum well structure at concentration below $6 \times 10^{19} \text{ cm}^{-3}$.

3. The method of claim 1 further comprising, during the introducing step,
introducing ions into a quantum well structure that includes:
a III-V material upper barrier layer;
a III-V material lower barrier layer; and
a III-V material quantum well layer.

4. The method of claim 3 further comprising, during the introducing step,
introducing ions into a quantum well structure that includes:
an InGaAsP upper barrier layer;
an InGaAsP lower barrier layer; and
an InGaAs quantum well layer.

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1 ~~5.~~³ The method of claim ~~5~~³ further comprising, during the introducing step,
2 introducing ions into a quantum well structure that includes:

3 an InGaAsP upper barrier layer;
4 an InGaAsP lower barrier layer; and
5 an InGaAsP quantum well layer.

1 ~~6.~~⁸ The method of claim 5 further comprising, during the introducing step,
2 introducing ions into a quantum well structure that includes:

3 an InP upper barrier layer;
4 an InP lower barrier layer; and
5 an InGaAsP quantum well layer.

6
7 ~~7.~~⁹ The method of claim ~~5~~³ further comprising, during the introducing step,
8 introducing ions into a quantum well structure that includes:

9 an InP upper barrier layer;
10 an InP lower barrier layer; and
11 an InGaAs quantum well layer.

12 ~~8.~~¹⁰ The method of claim ~~5~~³ further comprising, during the introducing step,
13 introducing impurity ions into a quantum well structure that comprises:

14 an AlGaAs upper barrier layer;
15 an AlGaAs lower barrier layer; and
16 a GaAs material quantum well layer.

17 ~~9.~~¹¹ The method of claim ~~5~~³ further comprising, during the introducing step,
18 introducing ions into a quantum well structure that includes:

19 an AlGaAsP upper barrier layer;
20 an AlGaAsP lower barrier layer; and
21 an AlGaAsP quantum well layer.

22 12. The method of claim 1 further comprising, during the introducing step,
23 introducing a deep-level ion species.
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1 13. The method of claim 12 further comprising, during the introducing step,
2 introducing a deep-level ion species selected from the deep-level ion species group
3 consisting of oxygen, gallium, fluorine, nitrogen, boron and argon.
4

1 14. The method of claim 1 further comprising, during the introducing step,
2 introducing arsenic ions.
3

1 15. The method of claim 1 further comprising, during the introducing step,
2 introducing xenon ions.
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1 16. The method of claim 1 further comprising, during the introducing step,
2 introducing phosphorus ions.
3

10 17. The method of claim 1 further comprising, during the introducing step,
2 introducing ions into a laser waveguide quantum well structure.
3

1 18. The method of claim 1 further comprising, during the introducing step,
2 introducing ions into a quantum well structure that further includes:
3

an upper cladding layer disposed above the upper barrier layer;

and introducing impurity ions into the upper cladding layer.

1 19. The method of claim 1 further comprising, during the introducing step,
2 introducing ions into a quantum well structure that further includes:
3

an upper cladding layer disposed above the upper barrier layer; and

4 introducing impurity ions into the upper cladding layer such that the impurity ions are
5 at least 0.5 micron from the upper barrier layer.

1 13-20. The method of claim 1, wherein the thermally annealing step is conducted at a
2 temperature above 450 °C for a time period in the range of about 2 seconds to about 3
3 minutes.

1 21. The method of claim 20, wherein the thermally annealing step is conducted at
2 a temperature above 600 °C, and

3 further comprising, during introducing step, introducing ions into a InP-
4 containing quantum well structure.

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1 22. The method of claim 21, wherein the thermally annealing step is conducted at
2 a temperature above 700 °C, and

3 further comprising, during the introducing step, introducing ions into a
4 GaAs-containing quantum well structure.

1 16. 23. The method of claim 1, wherein the introducing step employs an ion
2 implantation technique.

3 24. The method of claim 23, wherein the introducing step employs an
4 implantation energy in the range of 1 eV to 3 MeV.

1 18. 25. The method of claim 23, wherein the introducing step employs an
2 implantation energy of no more than 400 KeV.

3 19. 26. The method of claim 1, wherein the thermally annealing step induces a
4 bandgap energy shift of at least 60 meV.

1 27. The method of claim 1 further comprising, after the introducing step and
2 before the thermal annealing step, depositing a capping layer on the upper surface of the
3 quantum well structure.

4 28. The method of claim 1 further comprising, during the introducing step,
5 introducing ions into a quantum well structure that further includes a layer doped with a high
6 mobility impurity, the layer doped with a high mobility impurity being back-spaced by at
7 least 0.1 μm from at least one of the quantum well layer, the upper barrier layer and the lower
8 barrier layer.

1 29. The method of claim 1, wherein the introducing step employs an implantation
2 technique to introduce ions into a substrate that includes the quantum well structure such that
3 the ions are located at least 0.5 microns away from the quantum well structure.

1 30. The method of claim 1, wherein the introducing step employs an implantation
2 technique to introduce ions into a substrate that includes the quantum well structure such that
3 the ions are located less than 0.5 microns away from the quantum well structure.

1 ^{22.}
2 ~~31.~~ The method of claim 1, wherein the introducing step employs a focused ion
3 beam.

1 ^{23.}
2 ~~32.~~ The method of claim 1, wherein the introducing step employs a dense ion
3 plasma.

1 33. A method for shifting the bandgap energy of a predetermined portion of
2 quantum well layer comprising:
3 forming a patterned mask layer on a quantum well structure, the quantum well
4 structure including:
5 a first barrier layer;
6 a second barrier layer; and
7 a quantum well layer disposed between the first barrier layer and the
8 second barrier layer;
9 implanting ions into a predetermined portion of the quantum well structure, at
10 a temperature in the range of from about 200 °C to about 700 °C, using the patterned mask
11 layer as an implant mask; and
12 thermally annealing the quantum well structure,
13 whereby quantum well interdiffusion is induced and the bandgap energy of the
14 predetermined portion of the quantum well layer is shifted.

15 34. The method of claim 33, wherein the forming step forms a patterned stress-
16 inducing mask layer.

17 ^{25.}
18 ~~35.~~ The method of claim ²⁴~~33~~, wherein the forming step forms an SiO₂ patterned
19 stress-inducing mask layer.

20 ^{26.}
21 ~~36.~~ The method of claim ²⁴~~33~~, wherein the forming step forms a patterned stress-
22 inducing mask layer on a substrate that includes the quantum well structure and wherein the
23 patterned stress-inducing mask layer is formed of a material with a thermal coefficient of
24 expansion that is at least 10 times different than the thermal coefficient of expansion of the
25 substrate.

26 ^{27.}
27 ~~37.~~ The method of claim ²⁶~~36~~, wherein quantum well intermixing is induced with a
28 spatial resolution of less than 3 microns.

29 ^{38.}
30 ~~37.~~ The method of claim ²⁶~~36~~ further comprising, during the forming step, forming
31 a patterned mask layer that includes a plurality of patterned mask layer portions, each of the

3 plurality of patterned mask layer portions having a thickness that is different than the
4 thickness of the other patterned mask layer portions, and

5 during the implanting step, implanting ions into predetermined portions of the
6 quantum well structure using the patterned mask layer to control the penetration of ions into
7 the predetermined portions of the quantum well structure.

1 3938. A method for shifting the bandgap energy of a predetermined portion of
2 quantum well layer comprising:

3 forming a patterned stress-inducing mask layer on a quantum well structure;
4 implanting ions into a predetermined portion of the quantum well structure at
5 an elevated temperature, using the patterned stress-inducing mask layer as an implant mask;
6 and

7 thermally annealing the quantum well structure,
8 whereby quantum well interdiffusion is induced and the bandgap energy of the
9 predetermined portion of the quantum well structure is shifted with a spatial resolution of less
10 than 3 microns.

1 439. A method for shifting the bandgap energy of a quantum well layer comprising:
2 introducing ions into a quantum well structure at a temperature in the range of
3 from about 200 °C to about 700 °C, the quantum well structure including:

4 an upper barrier layer;
5 a lower barrier layer; and
6 a quantum well layer disposed between the upper barrier layer and the
7 lower barrier layer; and

8 thermally annealing the quantum well structure,
9 whereby quantum well interdiffusion is induced and the bandgap energy of the
10 quantum well layer is shifted

11 4140. The method of claim 42, wherein the introducing step employs a dose in the
1 range of $1 \times 10^{11} \text{ cm}^{-2}$ to $1 \times 10^{15} \text{ cm}^{-2}$ and an implantation technique with an implantation
2 energy in the range of 1 eV to 3 MeV.

1 41. A method for shifting the bandgap energy of a quantum well layer comprising:
2 introducing ions into a quantum well structure at an elevated temperature;
3 thermally annealing the quantum well structure,

4 whereby quantum well interdiffusion is induced and the bandgap energy of the
5 quantum well structure is shifted

1 ~~43~~42. The method of claim 44, wherein the introducing step uses an ion implantation
2 technique.

1 ~~44~~43. A photonic device assembly comprising:
2 a plurality of operably coupled photonic devices monolithically integrated on a
3 single substrate;

4 wherein the plurality of operably coupled photonic devices are formed using a method
5 that includes:

6 forming a patterned mask layer on a quantum well structure, the quantum well
7 structure including:

8 a first barrier layer;

9 a second barrier layer; and

10 a quantum well layer disposed between the first barrier layer and the
11 second barrier layer;

12 implanting ions into a predetermined portion of the quantum well structure, at
13 an elevated temperature, using the patterned mask layer as an implant mask; and

14 thermally annealing the quantum well structure,

15 whereby quantum well interdiffusion is induced and the bandgap energy of the
16 predetermined portion of the quantum well layer is shifted.

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18 ~~44~~45. The method of claim 43, wherein the elevated temperature in the range of
19 from about 200 °C to near the crystal damage temperature.

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21 ~~46~~45. The crystal damage temperature of claim 43 is about 750°C for InP/InGaAsP
22 materials and is about 950°C for GaAs/AlGaAs materials.

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24 ~~47~~46. The photonic device assembly of claim 43, wherein the plurality of operably
25 coupled photonic devices includes a low-loss waveguide, a 1x2 multi-mode interference
coupler, an optical amplifier, and an optical modulator.

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A-10
add
A-11